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13. ABSTRACT (Maximum 200 Words)

The objective of this project was to acquire instrumentation that will advance the state-of-the-art in real-time control and enhance the transition of new adaptive control techniques to DOD laboratories and industry. The instrumentation is portable in order to permit travel to DOD laboratories and industry to implement innovative controllers on their experimental testbeds. The key instrumentation is a special-purpose multi-processor configuration based on 4 Texas Instruments TMS320C40 60 MHz DSP processors and 4 DEC Alpha AXP 21164 500 MHz processors with 32 input channels and 32 output channels. The performance of this instrumentation extends the state-of-the-art in real-time computing for feedback control applications. A unique feature of this instrumentation is the fact that it is self-contained and fully transportable to allow on-site research in DOD laboratories and industry. The principal instrumentation was supplied by dSPACE, Inc., a vendor of real-time control processors. Of critical importance is their software interface to the Matlab real-time C code generator as well as their convenient diagnostic and interface software. Their multi-processor architecture allows real-time computing capability for feedback control beyond anything else currently available.

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A Real-Time Multi-Processor for Adaptive Control Experiments

Award Reference Number F49620-98-1-0224

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1 Overview of the Project

During the past two decades there have been enormous advances in control theory due largely to DOD funding in mathematics and related fields. This grant was used to purchase instrumentation for experimental control activities for facilitating the transition of these and future developments to real-world applications.

The objective of this project was to acquire instrumentation that will advance the state of the art in real-time control and enhance the transition of new adaptive control techniques to DOD laboratories and industry. The instrumentation is portable in order to permit travel to DOD laboratories and industry to implement innovative controllers on their experimental testbeds.

The key instrumentation we have purchased is a special-purpose multi-processor configuration based on 4 Texas Instruments TMS320C40 60 MHz DSP processors and 4 DEC Alpha AXP 21164 500 MHz processors with 32 input channels and 32 output channels. The performance of this instrumentation extends the state of the art in real-time computing for feedback control applications. A description of the project objectives is given later in the report.

A unique feature of this instrumentation is the fact that it is self-contained and fully transportable to allow on-site research in DOD laboratories and industry. We have already visited the Air Force Research Laboratory in Albuquerque, NASA Langely, and Lord Corporation. These visits allowed me to interact with DOD and industry personnel by exchanging ideas and undertaking joint research projects.

The principal instrumentation was supplied by dSPACE, Inc., a vendor of real-time control processors. dSPACE has an excellent understanding of real-time control requirements, and their processors are widely used in DOD and industry laboratories. Of critical importance is their software interface to the Matlab real-time C code generator as well as their convenient diagnostic and interface software.

dSPACE, Inc., has continually advanced the state of the art in real-time processing for feedback control applications. Their use of the DEC Alpha AXP 21164 processor in conjunction with the TI TMS320C40 processor provides considerable speedup over the use of the C40 alone. In addition, their multi-processor architecture allows real-time computing capability for feedback control beyond anything else available. This technology is the principal component of the DURIP instrumentation.

The Principal Investigator for this grant is Professor Dennis S. Bernstein. He is currently supported under grant F49620-98-1-0037 entitled "Experimental and Theoretical Techniques for Nonlinear Identification and Adaptive Cancellation." This grant has benefited from the acquired instrumentation.

2 Relevance of the Acquired Instrumentation to the DOD Mission

Control-system technology is essential for virtually all high-performance vehicles. Accordingly, advances in control-system engineering impact many of the concepts described in the *New World Vistas* report [1]. The report identifies the following technological advances as being important for the effectiveness and affordability of the Air Force of the future:

Large lightweight space structures. Such structures would provide the means for low-power, high resolution radar.

Laser satellite communication. This technology would provide high-bandwidth, unjammable, non-interceptible communcation between space assets.

High aspect-ratio wings. This is an enabling technology for dramatic improvements in heavy lift aircraft approaching 1,000,000 lbs.

Increased engine efficiency. Increasing engine efficiency by 20% is viewed as a feasible goal that would reduce the need for refueling and therefore increase global mobility.

Precision airdrop. The ability to deliver cargo from up to 20,000 ft with 50 ft accuracy would contribute to resupply and maneuver effectiveness.

All of these technological objectives depend upon control-system technology. In fact, the ability to realize many of these objectives will most likely depend upon major advances in control theory, algorithms, software, and hardware.

The *New World Vistas* report [1] focuses on "revolutionary" technologies that can provide a "quantum enhancement" to current capabilities. The report stresses that such enhancements correspond to a phase of development that often occurs 40-50 years after the introduction of a new technology. This observation applies as well to the development of control-system technology.

While current technology is the beneficiary of remarkable advances in control theory and technology, the implementation, tuning, and validation of control laws remains an expensive, difficult, and time-consuming task. Every system has different characteristics and every copy of the system requires careful, individualized tuning. I therefore believe it is time for a revolution in control technology that exploits the promise of *adaptive control*, that is, control algorithms that have the ability to learn and change in response to unexpected changes in the system and its environment. This ability would provide a "coming of age" for control technology without parallel since the advances in control made during WWII.

In practice, control-system engineers rely upon analytical and numerical models to understand the qualitative behavior of a system before it is built, and detailed empirical

data to predict the behavior of the actual system once it has been constructed. For aircraft, these phases correspond to computational fluid dynamics and finite element analysis before construction and wind tunnel and flight testing after construction. Adaptive control can simplify both of these engineering phases by overcoming the need for highly detailed dynamical models.

The benefits of adaptive control for aerospace applications, in particular, to the objectives from [1] listed above, can be enormous. Adaptive controllers can reduce cost, improve performance, and increase flexibility for all of these systems. For example, the need for detailed modal analysis of large space antennas and high aspect-ratio wings can be reduced, as can tedious mass properties analysis of spacecraft for precision pointing and air-dropped supplies for precision landing. In this way, adaptive control can have a major impact on the future effectiveness of the Air Force.

3 Prior Accomplishments in Experimentally Based Controls Research

The greatest challenge facing control researchers is the need to transition theoretical advances to operational systems. Therefore, in conjunction with my theoretical research, I have developed a laboratory for experimentally based control-system research. These activities have helped me to address implementation and hardware issues, and they have focused my theoretical research on problems of interest to DOD and industry. In addition, control experiments have frequently suggested new control techniques and basic research directions that might otherwise have been overlooked.

We have developed several control experiments to demonstrate and validate new control concepts, and we expect these activities to have a major impact on transitioning these ideas to applications. We have learned that experiments involving new control methods can reveal hidden strengths and weaknesses that are not apparent from theoretical analysis. What we learn from control experiments is invaluable for transitioning new ideas to practice.

The experiments we have developed include noise and vibration control experiments as well as rotating imbalance experiments. These experiments, which are described in the following section, comprise a diverse collection of challenging testbeds with relevance to DOD and industrial applications.

3.1 Acoustic and Structural Control Experiments

Active suppression of acoustic noise and structural vibration has undergone considerable development over the past two decades [2-14]. These problems are closely related and differ primarily in the frequency ranges and choice of sensors and actuators. Acoustic noise control involves the motion of fluids, while structural vibration control is primarily concerned with the motion of solids. Many applications involve both aspects through structural-acoustic

interaction. Potential and current applications of acoustic noise control technology include aircraft engine noise, submarine acoustic radiation, automobile interior noise, heating and air conditioning system noise, industrial machinery noise, and many other applications.

Active structural vibration control is directly relevant to New World Vistas objectives involving large lightweight space structures and high aspect-ratio wings. Both of these applications involve large flexible structures that are sensitive to disturbances. As another example, precision optical components, whether they be located on the ground, in the atmosphere, or in space, are sensitive to disturbances that can adversely affect phase properties. For example, systems such as airborne laser (ABL) can benefit from the use of active structural control to counteract the effects of vibration due to the aircraft engines, turbulence, and other disturbance sources.

3.1.1 Noise Control Experiments

Our experimental activities in active noise control have involved various acoustic configurations to investigate robust controllers on high-order lightly damped systems. To obtain model-based controllers we derived analytical models [15-17], and we applied identification techniques which proved to be efficient for controller design [18,19].

For noise control the most widely used techniques are based upon adaptive signal processing techniques [2-4,8,10,13]. Because these methods often utilize measurements of the disturbance, they are traditionally viewed as feedforward rather than feedback algorithms. Although feedback techniques have seen limited application to noise control problems, there is increasing interest in this approach [6,7,9].

The acoustic duct experiment helped us to understand the relationship between the feedforward and feedback control paradigms. Specifically, in [20] we showed that the physical arrangement of speakers and microphones in the standard feedforward setup effectively circumvents the limitations imposed by the Bode integral by minimizing the gain of the spatial component of the closed-loop transfer function. In fact, feedforward control strategies for minimizing the spatial component of the closed-loop transfer function have been used in the feedforward literature for broadband suppression [5].

From a feedback point of view, the post-adaptation performance of feedforward algorithms can be attributed to the "acoustic feedforward" arrangement of the measurement, control, disturbance, and performance signals, where typically the measurement is located near the disturbance and the control is located near the performance. This arrangement precludes nonminimum phase zeros in the disturbance-to-measurement and control-to-performance paths and thus permits asymptotically perfect cancellation as predicted by singular LQG theory. These fundamental observations have ramifications for the placement of sensors and actuators in noise and vibration control applications.

In control experiments we considered the case of noise in an acoustic duct, which can be viewed as a one-dimensional acoustic field. However, many real-world applications involve three-dimensional acoustic fields. While the basic physics is common to both cases, noise control in three-dimensions is significantly more challenging than in one dimension for

several reasons. First, a three-dimensional field has significantly higher modal density than a one-dimensional field. Specifically, whereas the number of modes in a given frequency band in a one-dimensional duct is proportional to the width of the frequency band, in three dimensions the number of modes per unit bandwidth is proportional to the *cube* of the frequency band. Thus the number of acoustic modes below 10 kHz in a typical room is enormous. In addition, the problem of suppressing noise in a three-dimensional acoustic space exacerbates the problem of "spatial spillover," that is, the inability to suppress noise uniformly throughout a three-dimensional volume.

In more recent work on active noise control we have focused on adaptive feedback disturbance rejection. In applications disturbances may arise from a wide variety of sources such as rotating machinery, which can cause tonal or multi-tone disturbances, as well as turbulence, which gives rise to broadband noise. Since modeling and identification are often difficult and expensive, and since the plant dynamics and disturbance spectrum may change during operation, our goal is to reduce the dependence of the control law on plant modeling requirements. This objective motivated our research on adaptive disturbance rejection reported in [21], which is based on an adaptive ARMA-type controller with recursive gain update. The attractive feature of the ARMARKOV adaptive control algorithm is the fact that it requires knowledge of only the transfer functions from the control inputs to the performance or error variables. Knowledge of the disturbance spectrum and transfer functions to other feedback sensors is not needed.

We have implemented the ARMARKOV adaptive control algorithm on an acoustic experiment with a variety of input disturbances. As shown in [21], with unknown single-tone and dual-tone disturbances, the experimentally measured closed-loop performance shows that the algorithm is highly effective in the presence of limited modeling information. For these experiments the controller was given no prior information about the disturbance spectrum, and only the transfer function from control to performance was identified prior to controller implementation. Experiments with sine swept disturbances showed that the algorithm has the ability to adapt rapidly to nonstationary disturbances. A numerical study reported in [22] shows that the algorithm possesses a high degree of robustness to modeling errors. In particular, we studied the case of a mismatch of the modal frequencies of the actual secondary path transfer function and the model used by the algorithm. While these numerical simulations indicated performance degradation, instability was not observed.

To achieve an even greater reduction in the need for off-line modeling, the acquired instrumentation has allowed us to implement more sophisticated adaptive disturbance rejection controllers. To do this, we implemented the ARMARKOV adaptive control algorithm with concurrent (that is, simultaneous) identification of the secondary path transfer function [23]. This implementation was achieved by dedicating one Alpha processor to adaptive gain update while another Alpha processor was devoted to secondary path transfer function identification as well as supervisory functions. The supervisory controller developed in [23] performs mode switching between control on/off, adaptation on/off, identification on/off, and control gain resetting. The resulting control algorithm can be implemented without prior identification of any kind so that it is effectively fully adaptive. While convergence results have not been developed for this hybrid direct/indirect algorithm, extensive simulation was carried out in [23] to illustrate its operation. Both the simulation and experiment showed promising results under a wide range of abrupt plant and disturbance perturbations.

The most challenging aspect is the importance of distinguishing between a significant change in the disturbance spectrum and a change in the secondary path transfer function. In the latter case, the supervisory controller employs an identification signal to update the model of the secondary path transfer function.

3.1.2 Electrostatically Controlled Membrane Experiment

In conjunction with Professor P. D. Washabaugh of the Aerospace Engineering Department of the University of Michigan, we developed a control experiment relating to lightweight precision optics. In this experiment an electrostatic potential of up to 2 kV is applied to a reflective mylar membrane to induce parabolic deflection of the membrane. Details of the experiment are given in [25]. The deformed membrane is intended to be useful as a reflective mirror surface [26,27].

In this application a challenging control problem arises from the fact that at large deflections (and small distances from the electrode) the membrane equilibrium is unstable. When instability occurs, the membrane contacts the electrode and a significant amount of current is discharged, thus damaging the membrane.

To obtain a better understanding of the control-system requirements for this kind of system, we developed an analogous experiment involving electromagnetic actuation and a restoring force provided by a spring. Because of the inverse-square-law nonlinearity of the electromagnet, this experiment captures the essential characteristics of the membrane instability.

We have already carried out control experiments on both the electromagnet and membrane testbeds. These control experiments have motivated the development of adaptive stabilization algorithms that are robust to unmodeled static nonlinearities [28,29]. The results given in [28] show that the adaptive stabilization algorithm gives excellent performance and robustness for a large class of nonlinear oscillators, while the experimental results given in [29] show that the controller is effective for the electromagnetically controlled oscillator in the presence of unknown inertia, damping and stiffness as well as input nonlinearities.

3.2 Rotating Imbalance Experiments

We have developed a series of experiments that address fundamental theoretical and practical issues that arise in rotational motion. In particular, we are interested in the use of active control methods for suppressing the effects of rotor imbalance. These experiments help to advance the state of the art in nonlinear and adaptive control while developing techniques for DOD and industrial applications.

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3.2.1 Rotating Actuator Experiment

The purpose of this experiment is to investigate the effectiveness of nonlinear control techniques for stabilizing oscillatory motion. The novel feature of this experiment is the use of a rotational actuator coupled to translational motion which introduces a kinematic nonlinearity [30]. Since the rotational actuator has no stroke limitation, it has potential advantages over linear proof mass actuators.

The experimental testbed involves a linear air slide with 4" of travel upon which is mounted a DC motor with an eccentric proof mass. Translational and rotational motion are measured using an LVDT (linear variable displacement transducer) and an optical encoder. Motor torque is commanded by means of a current-regulated servoamplifier, which in turn is commanded by a real-time control processor.

A wide range of control laws have been implemented on this experiment, including passivity-based designs, integrator backstepping, and virtual absorbers [31,32]. This experiment was also the focus of a Special Issue on a Nonlinear Benchmark Problem [33] which I edited for the International Journal on Robust and Nonlinear Control. This problem is also being used by researchers as an informative illustration of nonlinear control-design techniques [34].

3.2.2 Magnetic Bearing Experiment

Rotor imbalance induces vibrations through support bearings and thus is a universal problem in rotating machinery. Numerous techniques have been developed for addressing this problem within the context of magnetic bearing technology [35,36]. To investigate techniques for actively suppressing the effects of rotor imbalance, we developed a rotating imbalance experiment. In this experiment a shaft is spun at a high rate and a magnetic bearing is used to apply forces to the shaft to counteract the effects of imbalance. In our experimental setup we mounted the shaft vertically to avoid the need for shaft levitation and to focus on imbalance compensation.

In developing viable controllers for imbalance compensation we realized that accurate estimates of the inertia matrix of the shaft were difficult to obtain. In fact, any useful control strategy for counteracting rotor imbalance must be effective in the presence of unknown and possibly changing inertia. The strategy we adopted was physically motivated and sought to emulate the motion of passive weights confined to a fluid-filled annulus surrounding the shaft. While mechanical autobalancing devices based on this principle have been known since the 1930's, we developed an adaptive virtual autobalancing feedback algorithm based on this idea [37-39]. The analysis in [37] shows that this algorithm incorporates an internal model of the disturbance arising from the mass imbalance. A more general technique developed in [40] is based upon Lyapunov function methods.

We experimentally implemented the adaptive virtual autobalancing algorithm on the rotating shaft experiment to assess its performance properties. In one experiment [39], we enabled the controller during spinup when the shaft reached 250 rpm, and then continued

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spinup until the shaft reached 1000 rpm. This experiment shows the ability of the algorithm to suppress the effects of rotor imbalance without prior or explicit on-line identification.

3.2.3 Control-Moment Gyro Experiment

As an extension of the work described above, we designed and constructed an actively controlled control-moment gyro (CMG). This testbed, which is described in [41,42], is a multibody dynamics and control experiment. Attached to a spacecraft and with a rapidly spinning rotor, a CMG uses nonlinear gyroscopic effects to provide stiffness for the spacecraft and, by applying torques to the gimbals, can be used to perform slewing maneuvers. In practice, however, CMG's often cause "wheel noise" due to imbalance which can impart disturbance forces to a spacecraft.

As can be seen in [41,42], the CMG involves an outer gimbal and an inner gimbal, both of which are actuated by motors. The inner gimbal is controlled by a matching pair of motors to double the available torque and to balance the motor mass. Attached to the inner gimbal is a fourth motor that drives a rotor. For control experiments, we can attach imbalance masses to the rotor to perform a variety of experiments including slewing and imbalance compensation.

The CMG experiment represents a significant control challenge. First, the physical device includes added mass and stiffness due to cables and connectors which are extremely difficult to model to a fine level of detail. This added mass and stiffness is expected to impact the dynamics of the system and thus must be accounted for by either identification or adaptive control. For a rotating spacecraft we have also developed a Lyapunov-based approach for adaptive command following that does not require prior identification of the inertia properties [43].

Another challenging aspect of the CMG experiment is the fact that it involves a system of rigid bodies whose inertia is not constant. Hence the dynamics of the CMG include both kinematic and gyroscopic nonlinearities. This challenge is more than academic since CMG's that are built for spacecraft are often limited in angular displacement to less than 20 degrees in order to reduce the complexity of the multi-body dynamics. In fact, allowing a larger range of motion would be useful for increasing the control authority of the CMG, while a full-range-of-motion CMG would alleviate the need for fuel to reset the wheel position. The CMG experiment thus has a direct connection to a problem of practical significance.

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5 Acquired Instrumentation

The instrumentation listed below was acquired under this grant. The associated costs are approximate. The Final Fiscal Report should be consulted for precise cost data.

1. Real-time parallel processor for controller implementation. Four TI TMS320C40 DSP 60 MHz processor boards, four DEC Alpha AXP 21164 500 MHz processor boards, 32-channel A/D board and 32-channel D/A board. 20-slot chassis. Cockpit and Trace software for control experiments. dSPACE, Inc. $93,300.

2. Scientific software for use with the dSPACE system. Mathworks, Inc. $1,000.

3. Shipping cases for real-time control processor (2). Custom designed to accommodate alternative equipment shipping configurations. Hardigg. $1,100.

4. PC laptop host for off-site control experiments. 166 MHz Pentium, 2.1 Gbyte hard drive, 16 Mbyte RAM. Toshiba model Tecra CDT. $3,850.

5. Data acquisition system. 4-channel input, 2-channel output, 32 MB memory, 102 kHz sampling rate. DSP Technology. Model Siglab 20-42. $8,300.

6. Low distortion function generator. Stanford Research Systems model DS360. $2,400.

7. Instrumentation amplifier, 3 channel, 200 kHz bandwidth, DC response. Endevco. $2,000.

8. Microphone preamplifier (3), 8 channels. Tascam model $1,000.